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THESIS

PROTECTION AGAINST A SHIP AS A WEAPON

by

Christopher D. Epp

September 2008

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PROTECTION AGAINST A SHIP AS A WEAPON

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

Stopping a ship commandeered and used as a weapon to attack shore infrastructure in the Strait of Malacca is a challenging problem. The purpose of this thesis is to determine systems that constitute architectures of an SoS to stop oil tanker that is hijacked with the intention of running into the oil terminal on Jurong Island, Singapore. In addition, this research aims at laying a sound systems engineering foundation for addressing this problem. The approach primarily leverages the System of Systems Architecture Development Process (SoSADP) [1]. Systems to stop hijacked merchant vessels or ships used as weapons (SAW) are investigated. This thesis shows that there are means to stop a SAW. These include existing and postulated systems that warrant further consideration and study for inclusion into Singapore's Maritime Domain Protection (MDP) architecture. The results of the research cited in this thesis have potential MDP applications around the world and can serve as tools for decision makers in future SAW and MDP analysis. All products in this thesis can be expanded in the future as part of the iterative systems engineering process.

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EXECUTIVE SUMMARY

Terrorists have demonstrated their intent and capability to execute attacks on oil related infrastructure. Singapore is considered an attractive target for such attacks, because a successful attack interrupting its extremely high throughput of oil flow of oil would certainly disrupt world oil markets and because the high traffic density of merchant ships transiting the Straits of Malacca and Singapore afford terrorists the opportunity to run a commandeered large merchant vessel into on oil related infrastructure.

This type of threat, known as a ship used as a weapon (SAW), was addressed in *Maritime Domain Protection in the Straits of Malacca* [2] by NPS's Systems Engineering and Analysis (SEA) Cohort 7 (SEA-7) in June 2005 and in *Maritime Threat Response* [3] by SEA-9 in June 2006. SEA-7 focused on an SoS for cargo container inspections and a total maritime inspection subsystem to detect and identify dangerous materials [2]. SEA-9 focused on an SoS to respond to maritime threats such as weapon of mass destructive on a ship, a SAW, and small boat attacks in San Francisco Bay [3]. Recently, the Temasek Defence Systems Institute (TDSI) raised this SAW problem at the TDSI-NPS conferences June 2007 and sought its solutions [4].

This thesis examines the modes-of-defeat for a SAW and develops conceptual systems, concepts, or methods as part of an family of systems (FoS) that can be employed in a system of systems SoS to stop an oil tanker used as a weapon before it can collide with the Jurong Oil Terminal in Singapore Harbor. The SoS is designated as the anti-SAW (ASAW) SoS. A Design Reference Mission [5] analysis indicates that the largest oil tanker registered with Singapore traveling at $25\ kts$ is used as a SAW.

The approach to determining architecture alternatives of the ASAW SoS leverages the System of Systems Architecture Development Process (SoSADP) [1]. It is set in motion by the SAW problem and ends with architecture alternatives of the ASAW SoS. The systems of the ASAW SoS are drawn from the FoS. The members of this FoS

have one function in common – that is stop a SAW, and they can be current and future systems and concepts. As the C3 structure remains fixed for all SoS architecture alternatives, the focus of this thesis is on the members of the FoS.

Since the mission of the ASAW SoS is to stop the SAW and to stop it as early and distant from Singapore as possible, the probability of mission kill, P_K, is the Measure of Effectiveness (MOE). The time from confirmation of a SAW to the time of mission kill, T_K, and the distance along its projected track from the Jurong Oil Terminal to the location where the SAW mission kill occurs, D_K, are the Measures of Performance (MOP) characterizing how well the mission kill is achieved.

The members of the FoS carry out these functions: Interrupt Air Flow, Degrade Personnel, Degrade Visibility, Impede Motion, Change Buoyancy, and Impede Steering. Interruption of the air flow of a SAW means to deny air for combustion to ships or to clog exhaust ducts. Degrading personnel refers to subduing or eliminating the commandeering terrorists. Degrading visibility refers to diminishing the line-of-sight visibility of the human eye. Changing buoyancy pertains to decreasing the “effective buoyancy” of the ocean water. Impeding steering pertains to denying a ship its ability to steer by applying sufficient counter torque or physical degradation of the rudder.

The resulting ASAW SoS architecture alternatives have both existing and postulated systems in the FoS. The existing systems include Sea Marshals, warships, aircraft, tugs, physical barriers, and artificial obscurants. Sea Marshals perform Degrade Personnel. Warships, waterborne vessels designed for military or law enforcement purposes, can perform many different functions as part of a larger ASAW system such as Interrupt Air Flow, Degrade Personnel, Impede Motion, Change Buoyancy, and Impede Steering. Tugs would carry out Impede Motion and Impede Steering, but traditional working tugs may not have the required speed. Similar to warships, fixed wing and rotary aircraft can provide many different functions such as Interrupt Air Flow, Degrade Personnel, Impede Motion, Change Buoyancy, and Impede Steering. A large-scale physical barrier could carry out Impede Motion by blocking the approaches to Singapore. Artificial obscurants can perform Reduce Visibility to reduce visibility of the approaches to Singapore.

Postulated systems, which tend to have a low TRL, exist only as concepts or require major modifications or development before they can perform the ASAW or any other MDP mission. The postulated systems are standing water waves, bubbling system, UUV, and air flow interrupter. A standing water wave that can be generated to deflect or redirect a waterborne craft base can perform Impede Motion and Impede Steering. An array of pipes or some other mechanisms to create rising gas bubbles could perform Change Buoyancy by reducing the density of the seawater. Unmanned Underwater Vehicles (UUV) could perform Impede Motion or Impede Steering by fouling the propeller or steering gear. Finally, an air flow interrupter possibly delivered by a guided means could perform Impede Motion by deny sufficient main engine air intake or exhaust.

Different combinations of the existing and postulated systems generate the architecture options where each unique combination constitutes an option. Existing and postulated architecture options are ranked separately but postulated options include existing systems. Option rankings are based on the technology and performance risks for their respective component systems. The resulting rankings are not an absolute order of priority but are a basis for formulating courses of action in ASAW SoS development.

The results generated by the SoSADP in this thesis can be applied not only to the ASAW mission problem but also to other MDP missions. Whereas the setting of the ASAW scenario is Singapore, the methods and solutions formulated in this thesis could apply to other crucial ports and shorelines around the world. Employing these solutions could negate such an attack, thereby protecting critical coastal infrastructure. Providing this protection would help maintain economic and political stability.

There is potential for near-term improvement of the existing options. It is recommended that continued analysis be conducted for high speed tugs, barriers, and obscurants for evaluating their integration into the current MDP SoS. Further analysis is also required and suggested for the postulated options. By their nature, postulated systems require extensive research and development. Additional study and research are

strongly recommended on existing and postulated systems for any nation where a SAW has been determined to be a significant threat. Finally, any future studies should extend beyond the SAW problem and include the overall MDP mission.

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I. INTRODUCTION

A. BACKGROUND

Terrorists are continuously looking for new ways to garner attention and wreak havoc on the United States and western civilization. It has long been known that disruption of the oil industry is an effective means to hinder the countries that depend heavily on oil products. After the first Gulf War, oil wells were set ablaze causing environmental damage and economic disruption in the commodities markets. Currently, the threat of land based attacks on oil infrastructure continues as evident by attacks in Iraq and the Russo-Georgian conflict. Although difficult to achieve, waterborne attacks are also being used. In 2002, a French oil tanker was attacked resulting in the spillage of 90,000 barrels of oil. [6]

In 2004, recognizing the effectiveness of interrupting oil flow within the world markets, Osama bin Laden openly called for attacks on the oil industry in Iraq. The stated purpose of this strategy was to inflict economic damage upon the United States. In the following year, Ayman al-Zawahiri echoed bin Laden’s call on an international level. In December 2005, al-Qaeda attacked a large oil refinery in Abqaiq, Saudi Arabia. [7]

Terrorist have demonstrated that they have the intent and capability to execute attacks on oil related infrastructure. It is therefore important to consider oil infrastructure when examining critical infrastructure protection. One location warranting attention is Singapore and its associated oil infrastructure.

Singapore is considered susceptible to such attacks for several reasons. First and foremost, it has an extremely high throughput of oil, and a successful attack interrupting this flow of oil would certainly disrupt world oil markets. Second, such a disruption, even if temporary, would provide the publicity that terrorists desire. Also, the high traffic density of merchant ships transiting the Straits of Malacca and Singapore afford terrorists the opportunity to hijack a large merchant vessel and use it as a SAW.

As pirates have shown they can overtake ships in the Strait of Malacca, and terrorists can successfully plan major attacks like those in New York, Madrid, and London, it is reasonable to expect or conclude that terrorists are capable of commandeering a cargo ship and using it as a weapon. Authorities in Singapore and the United States acknowledged this threat, which was addressed in *Maritime Domain Protection in the Straits of Malacca* [2], by NPS's Systems Engineering and Analysis (SEA) Cohort 7 (SEA-7) in June 2005 and in *Maritime Threat Response* [3] by SEA-9 in June 2006. SEA-7 focused on an SoS for cargo container inspections and a total maritime inspection subsystem to detect and identify dangerous materials [2]. SEA-9 focused on an SoS to respond to maritime threats such as WMD on a ship, a SAW, and small boat attacks in San Francisco Bay [3].

The Temasek Defence Systems Institute (TDSI) continues to raise this problem at the TDSI-NPS conferences June 2007 and seeks solutions [4]. This thesis attempts to provide solutions and facilitate further study on precisely how to stop a SAW. Additionally, maritime inspection, cost-effectiveness, national response are not within the scope of this work. Solutions to stop a ship as a SAW are investigated. The objectives of this work are to lay a solid systems engineering foundation for addressing the SAW problem and to include the initial research and analysis necessary to develop methods specifically to stop a hijacked oil tanker with the intention of running into the oil terminal on Jurong Island, Singapore. The goal of this thesis is to investigate methods to deal with such a threat.

B. PROBLEM STATEMENT

This thesis examines the modes-of-defeat for a SAW and develops conceptual systems, concepts, or methods as part of an FoS that can be employed in a SoS to counter a SAW in Singapore. Again, Singapore serves as the setting for this study. A cargo ship in the vicinity of Singapore is assumed to have the intention of colliding with Jurong Oil Terminal in Singapore Harbor.

C. APPROACH

The approach to determining those methods or systems primarily leverages the *System of Systems Architecture Development Process* (SoSADP) depicted in Figure 1 [1].

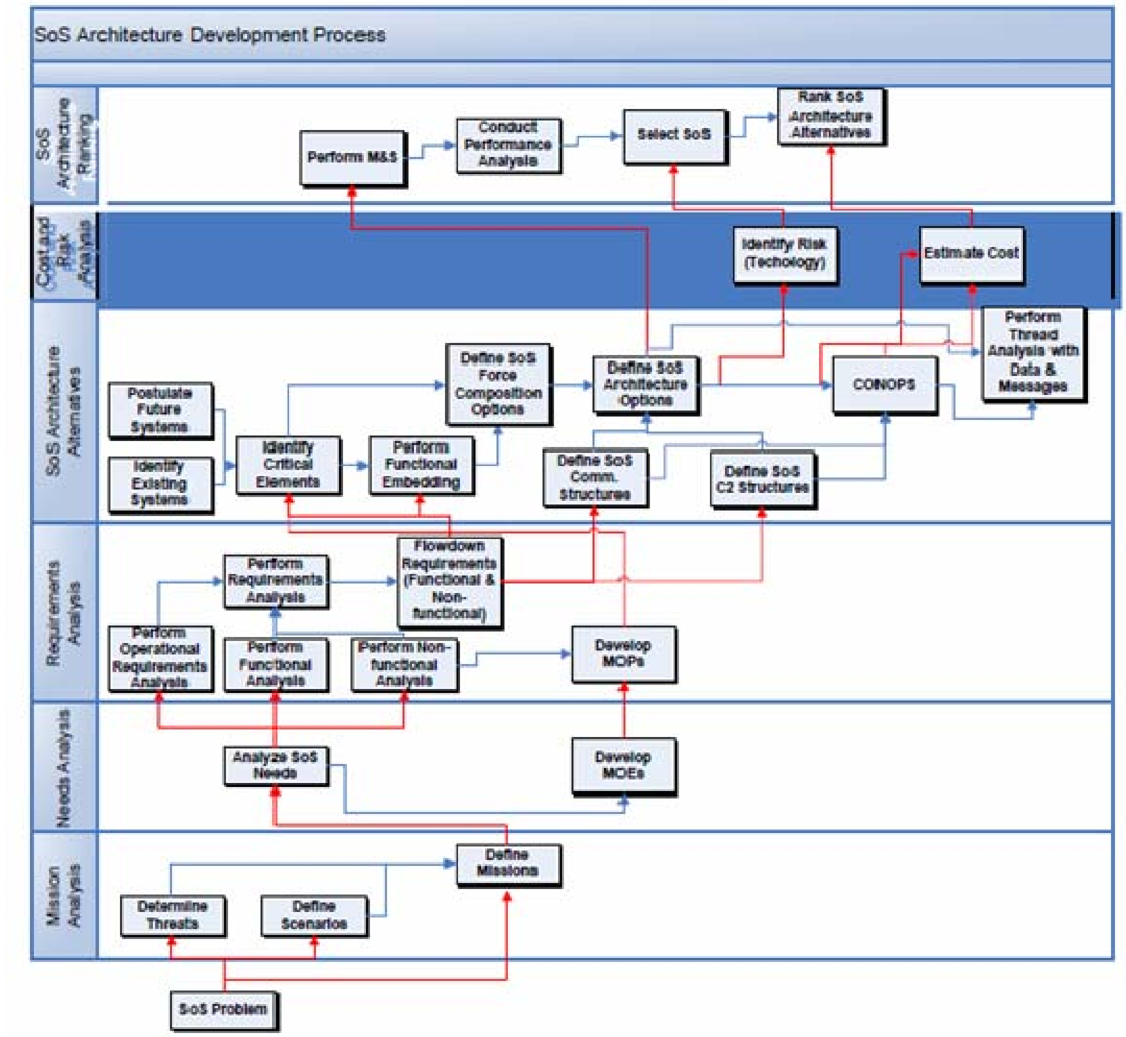

Figure 1. The layered structure of the SoSADP (From: [1])

1. System of Systems Engineering Methodology

Systems of Systems (SoS) Engineering involves taking an SoS engineering problem and formulating solution systems of systems that consist of current and future systems. The main motive for having an SoS over a monolithic stand-alone system is to achieve capabilities that cannot be achieved by individual stand-alone systems. One

major contrast between an SoS and a monolithic system is that the loss of one or more systems constituting an SoS does not necessarily mean the SoS completely loses its capability, whereas a system losing one of its components will likely experience major degradation in capability. Since the purpose of the SoS treated in this thesis is to counter a SAW, it is designated as the anti-SAW (ASAW) SoS.

The SoSADP is a systems engineering process used to arrive at SoSs employed to stop a SAW. It is a layered process in which the processes of a layer provide input to the layer above it, as shown in Figure 1. As a framework for analyzing solutions to the SAW problem, the SoSADP starts with the problem of stopping a SAW and ends with architectures of SoS to carry out the ASAW mission. The systems of an ASAW SoS will be drawn from a family of systems (FOS). The members of this FoS have one function in common – that is stop a SAW. They can be current and future systems and concepts. An ASAW SoS composed by the elements of this FoS will not materialize unless they have the capability to stop a SAW. The focus of this thesis thus will be on the members of the FoS.

2. SoS Problem

The SoS problem is to stop a SAW before it can achieve its mission. Specifically, the problem is to stop an oil tanker used as a SAW before it can collide with the Jurong Oil Terminal in Singapore. This problem statement sets in motion the SoSADP.

3. Mission Analysis

Mission analysis is comprised primarily of the Design Reference Mission (DRM). The process for DRM development is based on *Laying the Foundation for Successful Systems Engineering* [5]. The philosophies and practices in [5] are used by the U.S. Navy in various acquisition programs are used in this work.

The DRM provides the basis for all subsequent systems engineering activities and is viewed as a living document that matures with iterations in the systems engineering process [5]. The DRM formally establishes the anticipated threat and operating

environment and captures the Determine Threats, Define Scenarios, and Define Missions processes within the Mission Analysis layer of the SoSADP. Additionally, the DRM defines scenarios and missions via Operational Situations (OPSIT).

4. Needs Analysis

After Mission Analysis, the process continues with Analyze SoS Needs. The SoSADP determines what the SoS must do to complete its purpose – to stop a SAW within the context of the DRM. It is the results of the Needs Analysis that generate the requirements for an ASAW SoS.

Technical Measures (TM) are generated based on guidance provided in *Technical Measurement* [8] and concepts from *The Fundamentals of Aircraft Combat Survivability* [9]. Measures of Effectiveness (MOE) are selected from the TMs.

5. Requirements Analysis

The established needs support the Requirements Analysis layer in which the requirements and Measures of Performance (MOP) are developed. Since this work focuses on the means to stop a SAW, the Requirements Analysis layer primarily addresses functional requirements of the FoS [1]. The SoS is to consist of the systems of the FoS that satisfy one or more of the functional requirements to stop the SAW.

6. SoS Architecture Alternatives

The SoS Architecture Alternatives are solution sets to be considered for solving the SAW problem. They are derived from Postulate Future Systems and Identify Existing Systems within the context of the input from Requirements Analysis. Communications Structures and Command and Control Structures are subsumed into one Command, Control, and Communications (C3) Structure and are assumed satisfactory and constant for each SoS architecture alternative. An in-depth analysis of C3 is not within the scope of this thesis. The FoS provides different combinations of systems, which, together with an invariant C3 structure constitute alternative SoSs.

7. Risk Analysis

The Cost and Risk Analysis layer of the SoSADP is confined to Risk Analysis. The cost of various architecture alternatives is not examined because it does not affect the methods for stopping a SAW. The functionality and performance of an FoS is of primary concern; cost is not within the scope of this thesis.

Risk Analysis is limited to identifying Technology Risk as it relates to each system in the FoS and Operational Risk within the CONOPS. Identification of Technology Risk is achieved by applying Hardware Technology Readiness Level (TRL) definitions from the DoD *Technology Readiness Assessment Deskbook* [10].

8. SoS Architecture Ranking

Perform Modeling and Simulation is not within the scope of this thesis. The SoS Architecture Ranking is achieved by comparing and contrasting the TMs associated with each architecture alternative to the fullest extent possible. Since the work in this thesis conceptual and is considered as a first iteration of the SoSADP, quantifying all TMs is challenging and not always possible. Reasonable assumptions and estimations are made to facilitate the analysis and, ultimately, the ranking of the SoS architectures and recommendations.

II. MISSION ANALYSIS

A. BACKGROUND

In the SoSADP, Mission Analysis is realized by Determine Threats, Determine Missions, and Define Scenarios. In this thesis, Mission Analysis and its component processes are achieved via a DRM. A DRM defines the threat and the operational environment in which the threat exists. Also, the DRM establishes the basis for subsequent systems engineering activities, particularly generating requirements, refining problem definition, developing concepts, analyzing alternatives, and testing and evaluation. In creating a DRM, the primary objective is to describe the threat and environment sufficiently. Identification of the solution is conducted as part of the SoSADP in later processes. A well-developed DRM facilitates the generation of requirements and subsequent system design, e.g., the system must operate within the environmental extremes. The construction of this DRM follows *Laying the Foundation for Successful Systems Engineering* [5], the philosophy and practices espoused in which are used by the U.S. Navy in various acquisition programs.

B. DRM: OPERATING ENVIRONMENT

1. Geography

The setting of this study is the Straits of Malacca and Singapore and the nautical approaches to Singapore. Figure 2 shows the Straits of Malacca and Singapore where the Andaman Sea is north-west of the Strait of Malacca and the South China Sea is to the east of the Strait of Singapore. Figure 3 shows Singapore and its nautical approaches. The nautical approaches are waterways such as straits, channels, harbors, and traffic separation schemes that allow for waterborne access to Singapore.

Figure 2. Map of Straits of Malacca and Singapore (After: [11])

Figure 3. Map of Singapore and its approaches (After: [11])

2. Maritime Conditions

Unlike the English Channel, the maritime conditions are comparatively benign. Although the seas and harbor can become choppy, they typically do not experience significant swells. Surface water temperature is also relatively stable throughout the year varying approximately 11^{o}F between day-night extremes. However, currents can reach up to 4.0 *kts* in the straits. This is comparable to the Gulf Stream, one of the larger open ocean currents. Table 1 summarizes the maritime conditions in the vicinity of Singapore.

Table 1. Summary of maritime conditions (From: [2], [12], [13])

Maritime Parameter	Maritime Condition	
Sea State	Straits of Malacca and Singapore	1-2, 3(max)
Water Temperature	Day Night	88^{o}F 79^{o}F
Currents	Straits of Malacca and Singapore	4.0 *kts* (max)
Tides	Mean High Water Mean Low Water	$2.0-2.9$ *m* $0.4-1.2$ *m*

3. Climate and Meteorological Conditions

The climate is described as: equatorial, hot, humid and rainy. Appendix A provides complete climatology directly from Singapore's National Environment Agency [14]. Monsoons occur from November to March and June to September. Thunderstorms occur on 40% of the days throughout the year [14]. Table 2 provides a summary of meteorological conditions.

Table 2. Summary of meteorological conditions (From: [14], [2])

Meteorological Parameter	Meteorological Condition	
Temperature	Average Maximum Average Minimum Extremes	88 - 93^{o}F 73 - 79^{o}F 67 - 101^{o}F
Pressure	Extremes Diurnal Variation	1002.0 - 1016.9 hPa 4 hPa
Winds	Mean Surface December - April June - October	12 mph from south-east from north-west
Relative Humidity	Mean Diurnal Range	84% 60 - 98%
Precipitation	Average Annual Rainfall	92.8 inches
Ducting (for > 3GHz)	Surface Ducting Evaporation Ducting	15 - 20% of the time Continuous

C. DRM: POTENTIAL TARGETS

Due to its high volume of oil throughput, the Oil Tanking Odfjell Terminal on Jurong Island, Singapore, shown in Figure 4, is selected as the target for this DRM. Several terminals exist in Singapore. Among the terminals in Singapore, Odfjell Terminal is chosen to be a high value target for terrorists because of its potential environmental disaster and disruption of all shipping in Singapore.

Figure 4. Map of Jurong Island and Oil Tanking Odfjell Terminal (After: [11])

D. DRM: THREAT CHARACTERISTICS

Again, the specific threat is defined an oil tanker commandeered by terrorists and used as a weapon. This section describes oil tankers in general and those specifically registered in Singapore. The term “oil tanker” applies to any vessel transporting large quantities of crude oil, refined oil, or other oil products. A pictorial representation of a typical oil tanker is shown in Figure 5.

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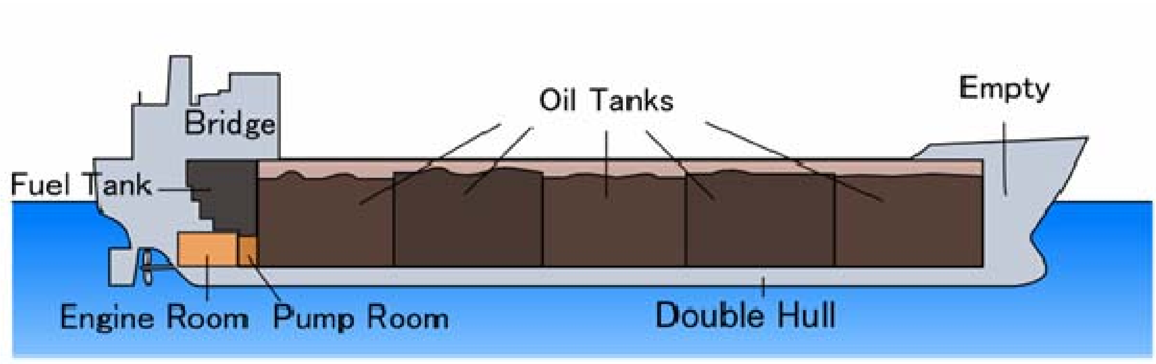

Figure 5. Pictorial representation of an oil tanker (From: [15])

As of January 2008, the largest oil tanker registered with Singapore is the crude oil tanker OCEAN JEWEL [16]. Table 3 provides a summary of OCEAN JEWEL's details. Appendix B shows the complete vessel details maintained by the International Maritime Organization (IMO) [17].

Table 3. Summary of OCEAN JEWEL details (From: [17])

Vessel Type	Crude Oil Tanker
Gross Tonnage (tons)	77,725
Summer DWT (tons)	147,143
Displacement (tons)	20,322
Speed (kts)	15.0
Length (m)	274
Breadth (m)	43
Depth (m)	24
Crew	17

1. Size

There are 334 oil tankers registered with Singapore. Of those 334, only eight are over 48 kGT. The remaining 326 are all under 32 kGT. Figure 6 is a histogram of oil tankers registered with Singapore, showing that the preponderance of oil tankers are less than 32 kGT. Although few ships are comparable in size to the OCEAN JEWEL, it is selected for the DRM and further analysis because it represents a worst-case scenario. [16]

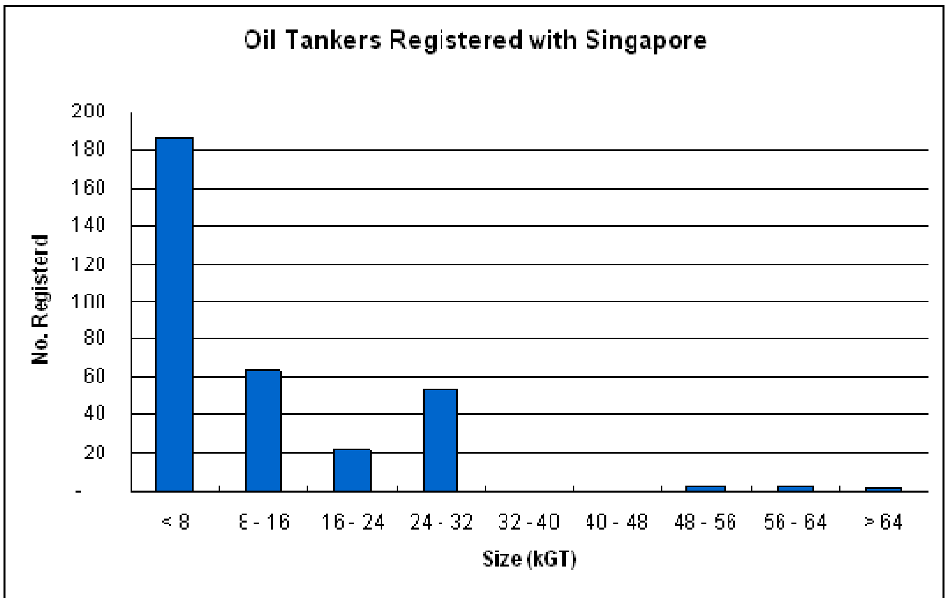

Figure 6. Oil tankers registered with Singapore (From: [16])

2. Speed

Traffic flow in the Strait of Malacca ranges from $14\ to\ 25\ kts$ and oil tankers typically transit at $15\ kts$ [18]. Whereas the IMO vessel data lists OCEAN JEWEL's speed at $15\ kts$, it is not deemed the maximum possible speed. A typical transiting speed for merchant vessels is $15\ kts$ for safe speed and fuel efficiency. For this DRM, the maximum possible speed is assumed to be $25\ kts$ in a worst case scenario.

3. Track

The scenario defines the track (Figure 7) as starting in the Straight of Malacca and ending at Singapore’s Odfjell Terminal. All OPSITs run along the same track, but the starting point may vary.

Figure 7. The track of a SAW in Strait of Malacca to Singapore (From: [11])

E. DRM: OPERATIONAL SITUATIONS (OPSIT)

1. Introduction

OPSITs are considered to be instances of a DRM in which the variables are attributes that make each OPSIT unique. The science and art of OPSIT development is similar to that of Testing and Evaluation (T&E) of major military systems. However, the process differs from T&E in that it can be as simple as formal “thought experiments.”

In developing a set or family of OPSITs, a balance is struck between the average and extreme situations. The “average,” “most likely,” or “benign” situation serves as a quality starting point for a baseline OPSIT. From this OPSIT, it is possible to do the “partial differentiation” (changing selected variables/attributes) to develop families or arrays of OPSITs. The attributes of OPSITs, such at starting location and vessel speed, are selected and varied in a manner that facilitates risk and performance analysis.

2. Assumptions

Assumptions are made to simplify the scenario and keep variables manageable and to facilitate estimations when actual data is not available. Assumptions must be realistic to lend plausibility to OPSITs. In choosing assumptions, the OPSIT developer must choose variables intelligently and ask the fundamental question, "What do I want to learn?" from a given OPSIT. Wisely selected assumptions also help to control growth in the total number of OPSITs. An example of an assumption in this thesis is that all SAW events occur during the day and originate in the Strait of Malacca. However, subsequent studies could examine night time scenarios or where a SAW originates in the South China Sea. Following are the assumptions and basic DRM information.

- Ship type: Crude Oil Tanker (OCEAN JEWEL)
- Location at detection: Straight of Malacca
- Target: Odfjell Terminal, Singapore
- Time of Detection: 0900L
- Speed at detection (SAD): Varies
- Speed profile: Constant
- Distance at detection (DAD): Varies
- Track: As shown in Figure 7
- Ship size; Constant
- Terrorist desire to remain undetected
- Terrorist are educated and will have maritime and navigation training
- Flow of traffic 15 *kts*
- Average weather conditions
- Average maritime conditions
- Unless otherwise stated, "distance" refers to distance along track
- Detection occurs within geographic region along track from northwestern limit of Strait of Malacca to Odfjell Terminal.

3. Characterization

For initial top-level OPSIT generation in this work, the two main characteristics to change will be Distance-at-Detection (DAD) and Speed-at-detection (SAD). To generate an initial family of OPSITs, each characteristic is assigned a high (H), medium (M), and low (L) value based on the relative probability of occurrence and potential level of impact or difficulty.

This assignment allows a manageable amount of OPSITs that sufficiently represent general situations. To characterize a particular OPSIT, a convention of OPSIT(DAD, SAD) will be used. For example, OPSIT(H, L) represents the OPSIT in which the SAW is detected near Singapore (high difficulty) transiting at a low speed (low difficulty). Table 4 shows the threat characteristics with associated difficulty level, value, and relative probability.

To develop the DAD difficulty level, detection is assumed to occur within 450 nautical miles (near the northeastern limit of the Strait of Malacca). The difficulty level is assigned by dividing this distance into thirds and designating the mean of each third as the respective value for the DAD's difficulty level. The probability of detection along the track is assumed to be uniformly distributed.

Table 4. Postulated Threat Characteristics

Characteristic	Difficulty Level	Value	Relative Probability (H,M,L)
Distance at Detection (DAD)	H	75 nm	M
	M	225 nm	M
	L	375 nm	M
Speed at Detection (SAD)	H	25 *kts*	M
	M	15 *kts*	H
	L	10 *kts*	L

Based on the typical observed rate of traffic flow in the Strait of Malacca, the medium difficulty level for the SAD is defined as $15\,kts$ and has an associated high relative probability [18]. As terrorists are assumed to wish to remain undetected, it is unlikely that a SAW would deviate significantly from $15\,kts$. Any large vessel transiting the straits at a speed of less than $10\,kts$ would quickly attract unwanted attention. Thus, a speed of $10\,kts$ is selected for a low level SAD with a low relative probability. Although some vessels transit the straits at $25\,kts$, terrorists presumably having a moderate amount of mariner proficiency would be less likely to transit at such a high speed because of the difficulties in collision avoidance, even though such a high speed would present a difficult situation for Singapore. Consequently, the relative probability of the SAW traveling at $25\,kts$ is assigned a medium value.

4. OPSIT Selection

Nine OPSITs result from combinations of the two DAD and SAD variables. OPSIT(M,M) is assumed as the baseline OPSIT and is not subject to further selection criteria. All DADs are equally likely to occur and all are therefore considered. Three OPSITs are withdrawn from consideration that have a low SAD, as they do not provide insight already provided by the other OPSITs.

As Skolnick advises that OPSITs feature one or more stressing operational characteristics, only OPSITS that contain at least one variable “H” will be considered, since “H” is defined as a stressing condition [5]. The OPSIT list (Table 5) consists of the following five scenarios.

Table 5. List of OPSITs

OPSIT List
OPSIT(H,H)
OPSIT(H,M)
OPSIT(M,H)
OPSIT(M,M)
OPSIT(L,H)

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III. NEEDS ANALYSIS

A. BACKGROUND

Needs Analysis is achieved by examining the threat, SAW, and establishing the needs of a SoS for stopping the SAW. The SoS is viewed as a counter-system to a SAW and is designated as an anti-SAW (ASAW) SoS. The needs of the ASAW SoS mirror the needs of the SAW. In order to develop MOEs, Technical Measures (TM) are identified and MOEs are selected from the TMs.

B. SYSTEM OF SYSTEM NEEDS

The fundamental mission of an ASAW SoS is to stop the SAW. The SAW is considered stopped when it no longer poses a threat to Singapore or its interests. When the SAW is stopped, a “mission kill” occurs and the SAW’s mission can no longer be achieved. In this thesis, the terms “kill” and “mission kill” are synonymous. [9]

Any system designed to counter another system must interrupt at least one or more of the needs of the attacking system. Thus, the needs for any given countermeasure are readily defined since the needs of the attacking system are already well known. Figure 8 depicts the needs of a SAW the point of view of an ASAW SoS. Specifically, the SAW needs to be able to stay afloat provided by buoyancy, to be steerable, to have air flow to maintain power, to be able to maintain forward motion, and to be manned by personnel who must have visibility to navigate the SAW.

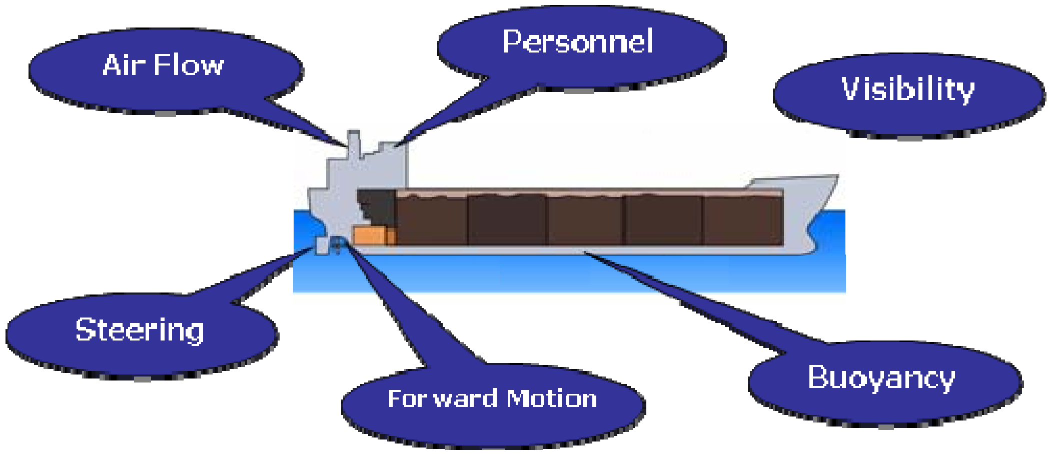

Figure 8. Needs of a SAW (From: [15])

Taking the converse of the SAW needs thus establishes the needs of an ASAW SoS. Every oil tanker need thus has a corresponding ASAW SoS need. The list of SAW needs (Table 6) serves as an initial list of "kill modes" by which a SAW can be defeated [9].

Table 6. Oil Tanker Needs

SAW Needs
Air Flow
Personnel
Visibility
Forward Motion
Buoyancy
Steering

C. MEASURES OF EFFECTIVENESS

1. Technical Measures

The four categories of Technical Measures (TM) enumerated in *Technical Measurement* [8] are MOEs, MOPs, Technical Performance Measures (TPM), and Key Performance Parameter (KPP). They are often confused and not thoroughly understood. This thesis uses [8] as a guide for technical measures. Figure 9 shows the relationship between TMs. TPMs and KPPs are not used in this work but their definitions from [8] are included for completeness.

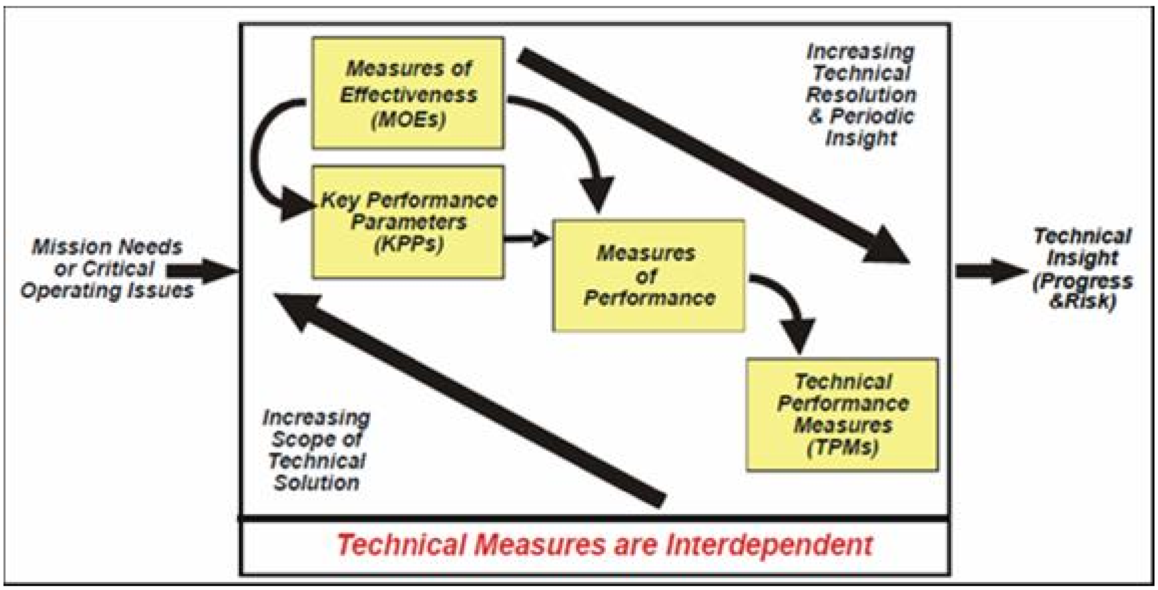

Figure 9. Relationships of the Technical Measures (From: [8])

- MOEs are “operational” measures of success closely related to the achievement of mission or operational objectives; i.e., they provide insight into the accomplishment of the mission needs independent of the chosen solution.
- MOPs characterize the physical or functional attributes relating to the system operation; i.e., they provide insight into the performance of the specific system.

- TPMs measure attributes of a system element within the system to determine how well the system or system element is satisfying specified requirements.
- KPPs are a critical subset of the performance parameters representing the most critical capabilities and characteristics.

2. Potential Technical Measures

The TMs include any parameters that provide value in the assessment of alternatives and the overarching systems engineering process [8]. The first step in generating TMs will be to examine the “kill tree” discussed in [9]. Appendix C shows the kill tree in its entirety. The kill tree gives probabilities of occurrence for particular events. These probabilities are adopted as TMs. Each event is defined in Table 7 and listed in Table 8.

Table 7. Kill tree event definitions.

Event	Description
A	Active weapon. Hijacking with intent to collide has occurred.
D	Detection. Authorities have confirmation of SAW.
L	Launch. ASAW has been activated.
I	Intercept. ASAW is within an engagement envelope as defined system.
H	Hit. Predefined interaction between SAW and ASAW occurs.
K	Kill. (SAW has been neutralized)

The progression of events in the kill tree gives time and distance intervals. These variables are also used as TMs. Figure 10 shows the progression of scenario events from left to right, starting with the occurrence of a hijacking, event A, and ending with a SAW mission kill, event K. The analysis starts at event D, a confirmed detection of a SAW.

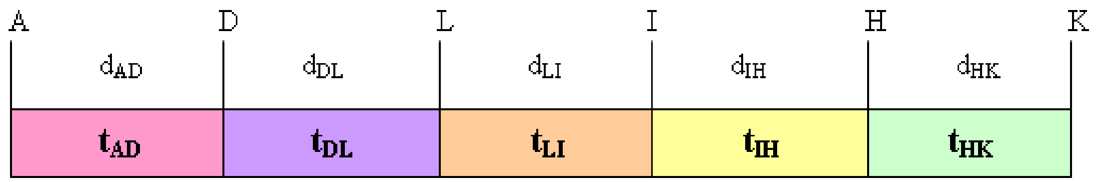

Figure 10. Progression of scenario events

The time elapsed and the distance between two events X and Y are denoted by t_{XY} and d_{XY} respectively. Let D_K be the distance along the track from the Odfjell Terminal to the SAW when it is killed, and T_K the time of the SAW kill. Then they can be computed according to Equations 3.1 and 3.2. Table 8 shows the list of TMs generated from the kill tree.

$$T_K = t_{DL} + t_{LI} + t_{IH} + t_{HK} \tag{3.1}$$

$$D_K = d_{DL} + d_{LI} + d_{IH} + d_{HK} \tag{3.2}$$

Table 8. List of Technical Measures

Technical Measures		
P_K	T_K	D_K
P_H	t_{HK}	d_{HK}
P_I	t_{IH}	d_{IH}
P_L	t_{LI}	d_{LI}
P_D	t_{DL}	d_{DL}
P_A	t_{AD}	d_{AD}

3. ASAW Measures of Effectiveness

The probability of kill, P_K, the chosen MOE, is a measure of an ASAW mission success (i.e., achieving SAW mission kill).

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IV. REQUIREMENTS ANALYSIS

A. BACKGROUND

Requirements Analysis is dependent on Needs Analysis and contains Operational Requirements Analysis, Functional Analysis, and Non-functional Analysis. The primary outputs of Requirements Analysis are the subsequent requirements and MOPs.

B. OPERATIONAL REQUIREMENTS ANALYSIS

The operational requirements are derived directly from the Problem Statement and the top-level need to stop a hijacked oil tanker or to stop the OCEAN JEWEL transiting at $25\ kts$ is viewed as a worst-case scenario.

As an operational requirement, the OCEAN JEWEL (SAW) must be stopped before it reaches the Jurong oil terminal. The goal is to stop the SAW in the Straits of Malacca and Singapore before it gets to the approaches to Singapore.

C. FUNCTIONAL ANALYSIS

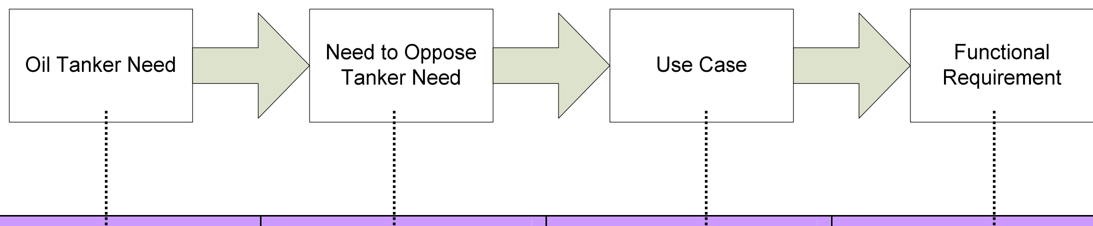
Functional Analysis involves identifying the top-level functions of the ASAW SoS and performing functional decomposition captured in a functional requirements diagram.

1. Functional Requirements

Most top-level functional requirements for the ASAW SoS are developed by with the aide of the use cases as suggested by Bruegge and Dutoit [19]. A use case expresses what a given system is doing from a given perspective at any given time. A complete set of use cases captures all possibilities of what a system should do. The use case method of requirements development views a given system as a “black box” depicting the actors, the system, system functions expressed as use cases and interactions between actors and use cases. [19]

Table 9 shows the process for crafting the initial list of ASAW FoS functional requirements and how they evolve, originating with oil tanker (SAW) needs. With the oil tanker needs and corresponding opposing needs for an ASAW SoS, the ASAW use cases are derived. The use cases are then mapped directly to the functional requirements.

Table 9. Functional Requirements development process



Oil Tanker Need	ASAW Need	ASAW Use Case	ASAW Functional Requirement
Air Flow	Interrupt Air Flow	Interrupt Air Flow	Interrupt Air Flow
Personnel	Degrade Personnel	Degrade Personnel	Degrade Personnel
Visibility	Degrade Visibility	Degrade Visibility	Degrade Visibility
Forward Motion	Impede Motion	Impede Motion	Impede Motion
Buoyancy	Change Buoyancy	Change Buoyancy	Change Buoyancy
Steering	Impede Steering	Impede Steering	Impede Steering

The resulting functional requirements are for the ASAW FoS. An ASAW SoS also needs to perform the C3 which is not shown in Table 9. The use case diagram in Figure 11 depicts the functional requirements, which include the C3 function, for an ASAW SoS. This view has two actors and one SoS. It is the FoS that interacts with the SAW. Table 10 also shows the functional requirements.

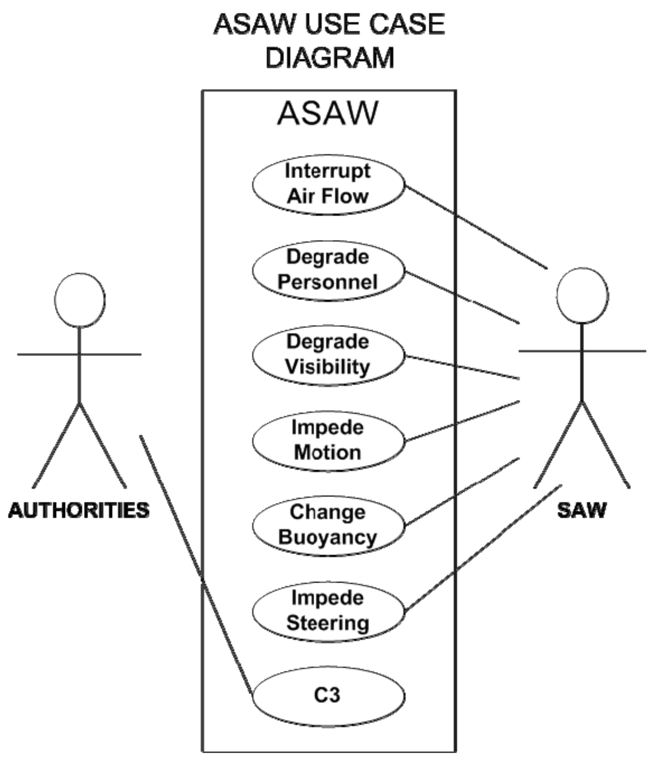


Figure 11. ASAW use case diagram

Table 10. ASAW SoS functional requirements

Functional Requirements
Interrupt Air Flow
Degrade Personnel
Degrade Visibility
Impede Motion
Change Buoyancy
Impede Steering
C3

2. Functional Decomposition

The SysML functional requirements diagram Figure 12 captures the functional decomposition. In addition to the sub-functions carried out to effect the corresponding top-level functions, the communicate sub-function allows for command and control by the C3 function.

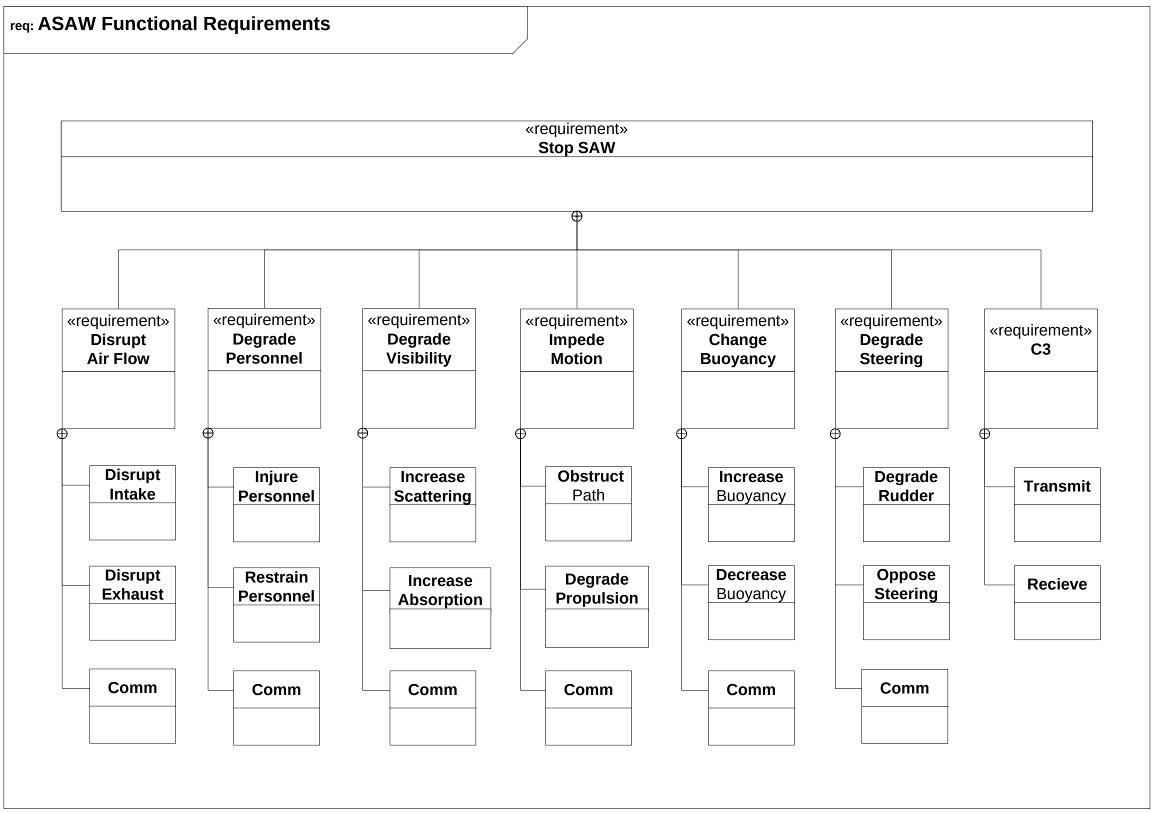


Figure 12. ASAW functional requirements diagram

D. NON-FUNCTIONAL ANALYSIS

The use case method is not appropriate for capturing non-functional requirements (NFR). NFRs may be referred to as “quality attributes” since they indicate how well a system performs its job.

The NFRs are data requirements, constraints, and quality requirements which relate directly to the ability of an ASAW SoS to stop a SAW [20]. The data and constraint requirements are obtained analytically using the fundamental laws of physics and available information. Focus is on the NFRs for the FoS, not the C3 function, as they relate to the functions required of the systems of the FoS that execute the stopping-the-SAW action.

1. Interrupt Air Flow

Interruption of the air flow of a SAW must consider intake/exhaust diameters, locations and required volumetric flow rates. There is no anti-ship system known to the author designed to deny air for combustion to ships or to clog exhaust ducts. This could be an effective "soft kill" method and may warrant further study for military use.

To illustrate this concept, a system reduces the intake air flow of a SAW to subsequently reduce its main engine power. The volumetric flow rate, Q_{in}, is given by

$$Q_{in} = A_{in} v_{in} \tag{4.1}$$

where A_{in} is the area of the intake duct and v_{in} is the speed of the intake air entering the duct. As Q_{in} is reduced, a certain decrease in engine power and speed is realized. When Q_{in} becomes sufficiently low, the internal combustion of the engines cannot be sustained, and the SAW will eventually stop moving.

Based on the specifications of the Pielstick 4.2/2V engine, a linear airflow-to-horsepower ratio of 2.6 in the region of high power [21], and an estimated maximum horsepower of the OCEAN JEWEL at $28{,}000\ HP$ [22], the maximum volumetric flow of approximately $72{,}800$ cubic feet per minute (CFM) is obtained. An air flow interrupting system would need to reduce this maximum volumetric intake flow.

2. Degrade Personnel

The International Maritime Bureau (IMB) reports indicate that the size of typical pirate teams range from two to fourteen [23]. Teams of 2-3 are on the low end and 10-15

on the high end, but usually teams of 5-6 pirates are used [23]. These numbers are used to gain insight into the number of terrorists required to commandeer a large merchant vessel.

Pirates are not as concerned about the crew working in the engineering spaces as hijackers would have to be in order to subdue all crewmembers and overtake their duties. Pirate teams vary mostly between 5 and 10 people when only cargo ships and tankers are considered [23]. Since hijacking and piloting a ship is more complicated than subduing and stealing from a ship, a team size range of 5-10 represents the minimum required by a terrorist team to execute a SAW mission.

3. Degrade Visibility

Degrade Visibility refers to diminishing the line-of-sight visibility of the human eye. Human visibility is subjective, but meteorological range is not and is expressed by Koschmieder's formula (Equation 4.2),

$$V = \frac{1}{\alpha} \ln \frac{1}{\varepsilon} = \frac{3.912}{\alpha}, \tag{4.2}$$

where V is the range, α is the extinction coefficient (at $0.55\ \mu\text{m}$ wavelength), and ε is the threshold contrast for detection assumed to be 0.02 [24].

Artificial obscurants may be utilized to deny a SAW's visibility of the entrance to the harbor from the straits or to deny visibility of the oil terminal itself. To this end, as the SAW gets closer to the harbor entrance, means can be used to increase the value of α and thereby reduce visibility.

4. Impede Motion

Impede Motion refers to degrading the forward axial motion of the SAW and not the ability to steer, which is addressed separately. Any system designed to block or interfere with the path of a ship must account for its momentum, kinetic energy, and thrust.

a. *Propulsion*

Sufficient counter thrust or physical degradation of the propeller must exist to deny a ship its propulsion. For an opposing thrust to be effective, the maximum forward thrust of the SAW, $T_{\max}$, must be known. Let $P_{\max}$ be the maximum power of the main engines and $v_{\max}$ the maximum speed of the SAW. Then $T_{\max}$ is given by

$$P_{\max} = T_{\max} v_{\max} . \tag{4.3}$$

With the maximum power of $28,000\ HP\ (21\ MW)$ and the maximum speed of $25\ kts\ (12.9\ m/s)$, it follows from Equation 4.3 that the maximum forward thrust for the OCEAN JEWEL is $1.6 \times 10^6\ N$.

b. *Path*

Let $p_{\max}$ be the maximum momentum, $m_{\max}$ the maximum mass, and $v_{\max}$ the maximum speed, and $K_{\max}$ is the maximum kinetic energy. Then, for the OCEAN JEWEL, whose mass is $167,465,000\ kg$ [17], its $p_{\max}$ and $K_{\max}$ are approximately $2.1 \times 10^9\ kg \cdot m/s$ and $1.37 \times 10^{10}\ J$ according to Equations 4.4 and 4.5, respectively.

$$p_{\max} = m_{\max} v_{\max} \tag{4.4}$$

$$K_{\max} = \frac{1}{2} m_{\max} v_{\max}^2 \tag{4.5}$$

If a barrier is to be constructed at the mouth of the harbor, then one measure of its effectiveness will be the amount the energy it can absorb without failing, assuming a SAW runs directly into it.

5. Change Buoyancy

Change Buoyancy pertains to decreasing the “effective buoyancy” of the ocean water. For a floating vessel, the net vertical force acting on it is zero. To make the net force on it non-zero, the density of the water, $\rho_{seawater}$, must be reduced significantly compared to the density of the SAW, ρ_{SAW}. If $\rho_{seawater}$ is less than ρ_{SAW}, the SAW will

lose its buoyancy. With the maximum volume of the OCEAN JEWEL, $V_{\max}$, being $219,962\ m^3$ [17], the density of the OCEAN JEWEL at maximum oil capacity is $760\ kg/m^3$, according to

$$\rho_{SAW} = \frac{m_{\max}}{V_{\max}}. \tag{4.6}$$

This method would only be effective for actually sinking or damaging a ship, which is not necessarily desired. It can be achieved by placing pipes on the ocean floor to release gas to aerate the water, and thereby, effectively reducing the density of the ocean water.

6. Impede Steering

Sufficient counter torque or physical degradation of the rudder must exist to deny a ship its ability to steer. For an opposing torque to be effective, the maximum turning torque, $\tau_{\max}$, must be known. Let Y_δ be the rudder angle coefficient, $\delta_{R\max}$ the maximum rudder angle (30^o), $F_{R\max}$ the maximum perpendicular turning force resulting from the maximum rudder deflection, and r_R the distance from the pivot to the rudder (Figure 13). The maximum torque, $\tau_{\max}$, is given by

$$\tau_{\max} = F_{R\max} r_R = Y_\delta \delta_{R\max} r_R \text{ [25].} \tag{4.7}$$

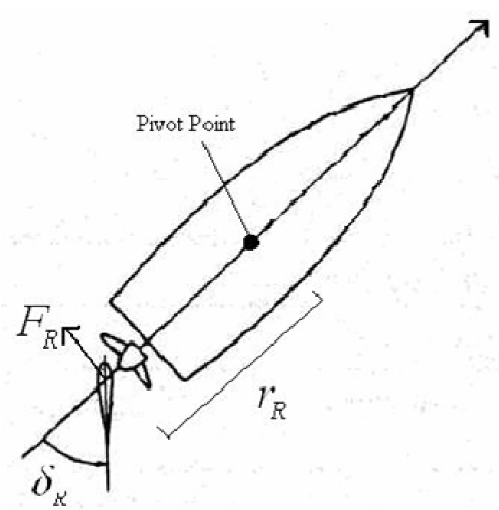


Figure 13. Rudder force diagram (From: [25])

Imagine a high speed tug boat that applies sufficient counter torque to deny the SAW its steering ability. If this tug is to simply prevent the SAW from steering (keep it going straight), then it must be able to match $\tau_{\max}$ of the SAW. An applied torque less than $\tau_{\max}$ degrades the ability of the SAW to steer, and any torque greater than $\tau_{\max}$ has a "redirecting ability."

E. MEASURES OF PERFORMANCE

1. Selecting and Specifying MOPs

Again, the mission of the ASAW SoS is to stop the SAW and to stop it as early and distant from Singapore as possible. The time from confirmation of a SAW to the time of mission kill, T_K, and the distance along its track from the Jurong Oil Terminal to the location where the SAW mission kill occurs, D_K, are selected as MOPs. Table 11 captures the MOE and MOPs.

Table 11. Table of MOE and MOPs

Technical Measure	Variable	Description
MOE-1	P_K	Probability of mission kill
MOP-1	T_K	Time from confirmation to time of mission kill
MOP-2	D_K	Distance along track from target to location of kill

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V. SYSTEM OF SYSTEM ARCHITECTURE ALTERNATIVES

An ASAW SoS makes use of existing and future systems in the FoS. The existing systems are those systems or platforms that may or may not be currently used for Maritime Domain Protection (MDP), may need some modifications, and are considered to have a relatively high TRL. The future systems pertain to those that exist only as concepts or require major modifications or development before they can perform the ASAW mission or any other MDP mission. The future systems tend to have a low TRL.

As the focus of this thesis is on the FoS, C3 structures are assumed to exist. An ASAW SoS will consist of elements from the FoS and the C3 structures.

A. IDENTIFICATION OF ELEMENTS

1. Existing Systems

a. Sea Marshals

Sea Marshals are a proactive and reactive system and perform the Degrade Personnel function. When performing reactively, they serve as a quick reaction force (QRF) that can be either waterborne or airborne. [2]

b. Warships

Generically, warships can provide many different functions as part of a larger ASAW system such as Interrupt Air Flow, Degrade Personnel, Impede Motion, Change Buoyancy, and Impede Steering. Warships are considered any waterborne vessel designed for military or law enforcement purposes. The mechanisms by which a warship achieves these functions may not be acceptable in that they result in undesired impacts to the environment and maritime traffic if oil is spilled or the SAW is sunk in a traffic lane.

c. *Tugs*

Tugs would carry out Impede Motion and Impede Steering, but traditional working tugs may not have the required speed. Schottle, a German based company, has designed a high-speed bridge erection vessel shown in Figure 14 [26]. Appendix D presents excerpts from Schottle's product information sheet**.** Whereas no high-speed tug is known to exist, the technology required for developing one is considered proven.

Figure 14. Schottle Bridge Erection Boat Type MB (From: [26])

d. *Aircraft*

Similar to warships, fixed wing and rotary aircraft can provide many different functions such as Interrupt Air Flow, Degrade Personnel, Impede Motion, Change Buoyancy, and Impede Steering. Again, the mechanisms by which these are achieved may not be acceptable for the same reasons mentioned in the discussion of warships.

e. *Physical Barrier*

No known physical barrier designed for the purpose of stopping a SAW exists. However, the flood gate in the New Waterway to Rotterdam (Figure 15) demonstrates that a large scale barrier blocking the approaches to Singapore could achieve the Impede Motion function effectively for a massive ship like the OCEAN JEWELL.

Figure 15. Flood gate in the New Waterway to Rotterdam (From: [27])

f. *Artificial Obscurants*

The military has designed artificial obscurants to deny the enemy full visibility of forces [24]. By fulfilling the Reduce Visibility function, a system of artificial obscurants could be employed to deny the terrorists piloting a SAW full visibility of the approaches to Singapore, thereby reducing the probability that the SAW could reach its intended target.

2. Postulated Systems

a. Standing Water Wave

The system concept to generate a standing water wave that deflects or redirect a waterborne craft is based on [28]. This concept can be effective in carrying out the Impede Motion and Impede Steering functions. Intuitively, a standing water wave system would be much more effective against smaller vessels not typical of a SAW. It could prove effectual in a counter Small Boat Attack (SBA) mission. In this case, it could perform the Degrade Personnel function if terrorists on a small boat encounter it at high speeds. This kind of system can be advantageous because it could be activated quickly upon the push of a button when the time to react is short.

b. Bubbling System

Fundamentally, this idea stems from the theory that the release of massive amounts of methane in the Bermuda Triangle may have contributed to the loss of some of the aircraft and ships [29]. Laboratory experiments have shown that continuous rising of small bubbles in water can sink floating objects [30] and such potential exists for military applications [29].

A potential system based on this concept might consists of an array of pipes or some other mechanism for releasing large amounts of gas over a large area. The bubbles of gas effectively reduce the density of the seawater and satisfy the Change Buoyancy function.

c. Unmanned Underwater Vehicle

Unmanned Underwater Vehicles (UUV) similar to those shown in Figure 16, developed by International Submarine Engineering [31], could be designed and programmed to foul the propeller or steering gear. Fouling the propeller or steering gear would perform the Impede Motion or Impede Steering functions. UUVs for this purpose are considered postulated systems because of the amount of development required to perform needed functions.

Figure 16. International Submarine Engineering UUVs (From: [31])

d. Air Flow Interrupter

An air flow interrupting system could be delivered with a guided weapon. An air flow interrupter could prove useful as a “non lethal” weapon since it is designed to deny sufficient main engine air intake or exhaust and the loss of human life would be unlikely. If intake air is on the side of the ship, then an air interrupting systems may be a man-portable or crew-served weapon deployed by a reaction force from a small boat.

B. FUNCTIONAL EMBEDDING

Functional Embedding allocates functions to elements (systems) comprising the ASAW SoS. Table 12 shows the functions performed by each existing and postulated system. The number of functions embedded per system is not a means to assess a system’s performance. With the exception of the C3 function, functional embedding determines the means by which each system can achieve a SAW mission kill.

Table 12. Functional Embedding

Functions / System	Interrupt Air Flow	Degrade Personnel	Degrade Visibility	Impede Motion	Change Buoyancy	Impede Steering	C3
Sea Marshals		X					X
Warship	X	X		X	X	X	X
Tug				X		X	X
Aircraft	X	X		X	X	X	X
Physical Barrier				X			X
Artificial Obscurant			X				X
Standing Water Wave				X		X	X
Bubbling System					X		X
UUV				X		X	X
Air Flow Interrupter	X						X

C. SYSTEM OF SYSTEMS COMPOSITION OPTIONS

SoS composition options are divided into existing and postulated options. The existing systems currently used as part of Singapore's MDP (Sea Marshals, warships, and aircraft) [2] are assumed remain in any existing force composition option. Therefore, all option variations involve combinations of tugs, barriers, and obscurants. Table 13 shows each option and its component systems where each option is indexed E-1 through E-8.

Table 13. Existing ASAW SoS composition options

System \ Option	E - 1	E - 2	E - 3	E - 4	E - 5	E - 6	E - 7	E - 8
Sea Marshals	X	X	X	X	X	X	X	X
Warships	X	X	X	X	X	X	X	X
Aircraft	X	X	X	X	X	X	X	X
Tugs		X			X		X	X
Physical Barrier			X		X	X		X
Artificial Obscurants				X		X	X	X

Postulated composition options may include existing systems and postulated systems. All existing systems are assumed to be included in all postulated composition options. All variations are combinations of standing water wave, bubbling system, UUV, and air flow interrupter. Table 14 shows all postulated ASAW FoS composition options where each option is indexed P-1 through P-16.

Table 14. Postulated ASAW FoS composition options

Option / System	P - 1	P - 2	P - 3	P - 4	P - 5	P - 6	P - 7	P - 8	P - 9	P - 10	P - 11	P-12	P - 13	P - 14	P - 15	P - 16
Sea Marshals	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Warships	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Aircraft	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Tugs	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Physical Barrier	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Artificial Obscurants	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Standing Water Wave		X				X	X	X				X	X	X		X
Bubbling System			X			X			X	X		X	X		X	X
UUVs				X			X		X		X	X		X	X	X
Air Flow Interrupter					X			X		X	X		X	X	X	X

VI. RISK ANALYSIS

A. BACKGROUND

Cost, schedule, and performance are the fundamental constraints in a program to develop a system. Any risks are ultimately related to at least one of these three constraints. In this work, Risk Analysis identifies schedule and performance risk by investigating technology risk and the TMs associated with each system in the FoS. The insight gained facilitates the ranking of the ASAW SoS architectures.

B. TECHNOLOGY RISK

In the DoD, Technology Readiness Assessments help to identify technology risk and serve as an aid to decision making in systems acquisition [10]. Identification of technology risk allows for a better understanding of both schedule and performance risk since it provides information on how well a certain system, technology, or concept is developed. If it is not mature or proven, then it is more likely to take a long time (schedule risk) to develop before it can meet functional requirements (technology risk).

To evaluate the technology risk for each existing and postulated system, each is scored using the DoD Hardware Technology Readiness Level definitions (Appendix E) [10]. Table 15 shows scorings for the respective systems.

Table 15. Technology Readiness Level scores

Existing systems	TRL	Postulated systems	TRL
Sea Marshals	9	Standing Water Wave	1
Warships	9	Bubbling System	3
Aircraft	9	UUVs	3
Tugs	7-8	Air Flow Interrupter	1
Physical Barrier	7-8	--	
Artificial Obscurants	7-8	--	

C. PERFORMANCE RISK

Identification of performance risk for each existing and postulated system is discussed based how each is or may be employed. Performance risks are assessed qualitatively by examining the MOE and MOPs, and where appropriate, the relative performance of the systems in the FoS is discussed. Impacts by these systems as they carry on their mission on the environment and shipping are not considered.

1. Sea Marshals

Sea Marshals are considered well trained, good at what they do, and a reliable "system" for defeating a SAW. Risk to P_K is thus low. The speed of sea and air platforms for Sea Marshals is an advantage. Risk is therefore related to the time from SAW confirmation to when marshals embark on a platform. The range at which Sea Marshals can be deployed is not a limiting factor. The risk in range exists only when a SAW is confirmed to be near Singapore as marshal teams may not be able to embark on their platforms quickly enough to execute their mission. Therefore, the risks in T_K and D_K are scenario dependant, increasing as the SAW speed increases and distance to the SAW at conformation decreases.

2. Warships

Warships are fully capable of stopping surface vessels. However, there are performance risks associated with each warship depending on its weapon systems. Thus, risk to P_K varies with the combat systems suite of a given ship. Since warships can transit as fast or faster than merchant vessels there is no risk in the warship's speed. The range of warships is also not a limiting factor and their time to intercept is dependent on the location and speed of the SAW. Again, the risks to T_K and D_K increase as SAW speed increases and distance to the SAW decreases.

3. Aircraft

Similar to warships, an aircraft's capability is dependent on its suite of weapons, and risk is therefore platform specific. Range and speed are not risks but advantages for aircraft. Limitations exist in the time from SAW notification to activation since it would take time for a crew and pilot to become airborne. All risk relationships are the same as those from warships.

4. Tugs

Risk to P_K is significant since tugs employed against a SAW may not fully achieve a mission kill but could prove effective in at least reducing a SAW's probability of success or mitigating its impact. Also, tugs are not designed to move non-cooperative vessels at transit speeds and may not have the required maneuverability. Traditional tugs are not designed for speed and are not on patrol in the straits. Risks to T_K and D_K exist because a tug's range is limited and crews would need time to get underway upon notification and may not be able to reach the SAW in time.

5. Physical Barrier

A physical barrier would be effective and there carries very little risk to P_K. A physical barriers performance is limited by the size of the ship it can stop or slow down. It is not feasible for a barrier system to be placed in the Straits of Malacca and Singapore and are therefore their use would be confined to the approaches to Singapore. A potential advantage of a barrier is its reaction time since it could be activated immediately upon SAW confirmation. The risk would exist in the time it takes to close because such a large system is expected to take tens of minutes to completely shut. Therefore there are negligible risks in T_K and D_K.

6. Artificial Obscurants

Artificial Obscurants would unlikely be an effective means of stopping a SAW but they could make navigation of the SAW difficult for the terrorists, thereby reducing

the probability that the SAW reaches the oil terminal. Risk also exists in that obscurants, dependent on prevailing winds at the time and location of deployment, may not achieve the required reduction in visibility. An advantage of obscurants, however, can be quickly activated and deployed from several locations. Risk to P_K is therefore significant and risks to T_K and D_K are relatively low.

7. Standing Water Wave

As previously discussed, performance risk of an ASAW system increases with the size of the SAW. It could be deployed anywhere along the ocean floor. The rate at which a standing wave generating system can be activated is expected to be near instantaneous, minimizing reaction time. Risk to P_K of such a system is difficult to assess. If this system were deployed, risks to T_K and D_K would be negligible.

8. Bubbling System

Similar to the standing water wave, risk increases as the size of the ship increases, specifically as the length and width of the ship increases. As the length and width of the SAW increases the area required for the bubbling system increases. There is little risk in where it can be used. The rate at which a bubbling system can be activated could be almost instantaneous. As with many postulated system risk to P_K is difficult to evaluate but risks to T_K and D_K are small.

9. Unmanned Underwater Vehicles

Risk in P_K exists in the ability of a UUV to search, track, and home-in on a SAW. It also exists in the ability of a UUV to foul the rudder or propeller. UUVs carry the same time and distance risks as do surface vessels. Risk is reduced as their speed and range is increased. Unlike manned vessels, time from SAW confirmation to being underway can be much shorter.

10. Air Flow Interrupter

The effectiveness of an air flow interrupter is dependent on the amount by which it can reduce air flow, intake or exhaust. There is risk associated with the ability to get an air interrupting apparatus in the proper location, which is also limited by the duration of time that it is able to keep the flow at low levels. Risk is also associated with its range and speed, and, it would be dependent on the launch platform location. However, an advantage is that air flow interrupters could be deployed by land, air, or sea based launching systems. The amount of risk to P_K is largely dependant on its delivery system and since guided weapons are reliable the risk to P_K is comparable to other postulated systems but the risks to T_K and D_K are low.

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VII. SYSTEM OF SYSTEMS ARCHITECTURE RANKING

Existing and postulated ASAW SoS architecture options are ranked separately. Rankings are based on risk (Chapter VI). Priorities and assumptions are discussed as the options are weighed against each other.

Recall that each ASAW SoS architecture option in Tables 13 and 14 in Chapter V is made up of the systems drawn from the FoS. Again, as the C3 structures remain unchanged across the ASAW SoS architecture options, ranking the ASAW SoS architecture options amounts to ranking the options described in Chapter V.

A. EXISTING SYSTEMS OF SYSTEMS RANKING

Options with the most systems are taken to be the best options if their component systems are equal. Adding any system to the ASAW SoS presumably makes the ASAW SoS better in all instances. The option with the most systems, E-8, is therefore ranked highest.

Since the TRLs are identical for tugs, barriers and obscurants, the differentiating factor among the three is their performance risk. Based on performance risk, barriers, tugs, and obscurants are ranked according to the order of appearance, which is the descending order of priority. Table 16 shows the ranking of the existing ASAW SoS architecture options corresponding to the respective compositions (E-1 through E-8).

Table 16. Existing FoS Ranking

Existing SoS Ranking	
Rank	**Option**
1	E-8
2	E-5
3	E-6
4	E-3
5	E-7
6	E-2
7	E-4
8	E-1

B. POSTULATED SYSTEMS OF SYSTEMS RANKING

Option P-17 has the most systems and is, therefore, preferred. Since the bubbling system and UUVs have equivalent TRLs and are not distinguished by their performance risk, they are considered equivalent in ranking. The standing water wave and air flow interrupter also have equivalent TRLs; however, the standing water wave would be less effective against a SAW, so the air flow interrupter ranks higher than the standing water wave. Table 17 captures the ranking of the postulate systems, predicated on, again, the presumption that adding any system to the ASAW SoS makes the ASAW SoS better in all instances.

Table 17. Postulated FoS Ranking

Rank	Option	Rank	Option
1	P-17	9	P-6
2	P-15	9	P-7
3	P-12	11	P-8
4	P-13	12	P-3
4	P-14	12	P-4
6	P-9	14	P-5
7	P-10	15	P-2
7	P-11	16	P-1

VIII. CONCLUSION

Terrorists have demonstrated their intent and capability to execute attacks on oil related infrastructure. Singapore is considered an attractive target for such attacks, because of its coastal oil infrastructure, high throughput of oil, high traffic density of merchant ships transiting the Straits of Malacca and Singapore, and high potential for a large economic impact if the oil flow and maritime trade are interrupted.

This type of threat, known as a ship used as a weapon (SAW), was addressed in Maritime Domain Protection in the Straits of Malacca [2] by NPS's Systems Engineering and Analysis (SEA) Cohort 7 (SEA-7) in June 2005 and in Maritime Threat Response [4] by SEA-9 in June 2006. SEA-7 focused on an SoS for cargo container inspections and a total maritime inspection subsystem to detect and identify dangerous materials [2]. SEA-9 focused on an SoS to respond to maritime threats such as weapon of mass destructive on a ship, a SAW, and small boat attacks in San Francisco Bay [3]. Recently, the Temasek Defence Systems Institute (TDSI) raised this SAW problem at the TDSI-NPS conferences June 2007 and sought its solutions [4].

This thesis examines the modes-of-defeat for a SAW and develops conceptual systems, concepts, or methods as part of a family of systems (FoS) that can be employed in a system of systems SoS to stop an oil tanker used as a weapon. The SoS is designated as the anti-SAW (ASAW) SoS. The specific scenario, established with the aid of the DRM analysis performed in this thesis, involves the largest oil tanker traveling at 25 kts and aiming to collide with the Jurong Oil Terminal in Singapore Harbor. .

The approach to determining architecture alternatives of the ASAW SoS leverages the System of Systems Architecture Development Process (SoSADP) [1]. It is set in motion by the SAW problem and ends with architecture alternatives of the ASAW SoS. The systems of the ASAW SoS are drawn from the FoS. The members of this FoS have one function in common – that is stop a SAW, and they can be current and future systems and concepts. As the C3 structure remains fixed for all SoS architecture alternatives, the focus of this thesis is on the members of the FoS.

The probability mission of kill, P_K, is the MOE. The time from confirmation of a SAW to the time of mission kill, T_K, and the distance along its projected track from the Jurong Oil Terminal to the location where the SAW mission kill occurs, D_K, are the MOPs. Selection of systems and the subsequent ranking of options depend on the MOE and MOPs.

The members of the FoS carry out these functions: Interrupt Air Flow, Degrade Personnel, Degrade Visibility, Impede Motion, Change Buoyancy, and Impede Steering. The resulting ASAW SoS architecture alternatives have both existing and postulated systems in the FoS. The existing systems include Sea Marshals, warships, aircraft, tugs, physical barriers, and artificial obscurants. The postulated systems are standing water waves, bubbling system, UUV, and air flow interrupter.

Technology and performance risks of component systems in an ASAW SoS form the basis for ranking the options. Technology risk identification scores each existing and postulated system based on DoD TRL definitions. Performance risk identification examines the MOE and MOPs, and where appropriate, the relative performance of the systems in the SoS. The evaluation of each system’s technology and performance risks result in rankings of SoSs composed of those sytems. The rankings are not to be taken as an absolute order of priority but rather as a basis upon which courses of action for defeating a SAW and enhancing MDP are formulated.

The results generated by the SoSADP in this thesis can be applied not only to the ASAW mission problem but also to other MDP missions. Whereas the setting of the ASAW scenario is Singapore, the methods and solutions formulated in this thesis could apply to other crucial ports and shorelines around the world. Employing these solutions could negate such an attack, thereby protecting critical coastal infrastructure. Providing this protection would help maintain economic and political stability.

There is potential for near-term improvement of the existing options. It is recommended that continued analysis be conducted for high speed tugs, barriers, and obscurants for evaluating their integration into the current MDP SoS. Further analysis is also required and suggested for the postulated options. By their nature, postulated

systems require extensive research and development. Additional study and research are strongly recommended on existing and postulated systems for any nation where a SAW has been determined to be a significant threat. Finally, any future studies should extend beyond the SAW problem and include the overall MDP mission.

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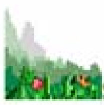
APPENDIX A. CLIMATOLOGY OF SINGAPORE [14]

Climatology of Singapore

Climate of Singapore

Singapore lies just north of the Equator near Lat 1.5 deg N and Long 104 deg E. Because of its geographical location and maritime exposure, its climate is characterised by uniform temperature and pressure, high humidity and abundant rainfall. The climate of Singapore can be divided into two main seasons, the *Northeast Monsoon* and the *Southwest Monsoon* season, separated by two relatively short inter-monsoon periods.



SEASONS:

North-East Monsoon Season - December to early March

Northeast winds prevail, sometimes reaching 20 km/h. Cloudy conditions in December and January with frequent afternoon showers. Spells of widespread moderate to heavy rain occur lasting from 1 to 3 days at a stretch. Relatively drier in February till early March. Also generally windy with wind speeds sometimes reaching 30 to 40 km/h in the months of January and February.

Pre South-West Monsoon - late March to May

Light and variable winds with afternoon and early evening showers often with thunder.

South-West Monsoon Season - June to September

Southeast/Southwest Winds. Isolated to scattered late morning and early afternoon showers. Early morning 'Sumatra' line squalls are common. Hazy periods.

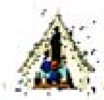
Pre North-East Monsoon - October to November

Light and variable winds. Sea breezes in afternoon. Scattered showers with thunder in the late afternoon and early evening.

TEMPERATURE: Diurnal range: Minimum 23 to 26 deg C and Maximum 31 to 34 deg C
Extremes: Minimum of 19.4 deg C and Maximum of 35.8 deg C

PRESSURE: Diurnal pressure variation of 4hPa. Maximum pressure usually occurring at 1100 and 2400 Local Time and minimum pressure occurring at 0500 and 1700 Local Time. Extreme pressures recorded are 1016.9 hPa and 1002.0 hPa.

RELATIVE HUMIDITY: Diurnal range in the high 90's in the early morning to around 60 % in the mid-afternoon. Mean value is 84%, During prolonged heavy rain, relative humidity often reaches 100 %.



RAINFALL: No distinct wet or dry season. Rainfall maximum occur in December and April. The drier months are usually in February and July.

APPENDIX B. OCEAN JEWEL DETAILS [17]

OCEAN JEWEL

IMO NUMBER	8809919
VESSEL TYPE	CRUDE OIL TANKER
HULL TYPE	SINGLE HULL
GROSS TONNAGE	77.725 tons
SUMMER DWT	147.143 tons
BUILD	1991
BUILDER	AESA MADRID - SPAIN
FLAG	SINGAPORE
MANAGER	OCEAN TANKERS SINGAPORE
OWNER	PUERTO REINOSA SHIPPING
INSURER	NORTH OF ENGLAND P&I U.K.

VESSEL DETAILS

CLASSIFICATION	+A1 TANKER FOR OIL ESP E0	
	LAST DRY DOCK	2006 Sep 30
	LAST SPECIAL SURVEY	2006 Sep 30
	NEXT DRY DOCK	2009 Jun 03
	NEXT SPECIAL SURVEY	2011 Nov 20
GENERIC	SPEED	15,0 knots
DIMENSIONS	BOW TO BRIDGE	234,30 m
	BREADTH EXTREME	43,20 m
	BREADTH MOULDED	43,20 m
	DEPTH	23,80 m
	DRAUGHT	16,37 m
	FREEBOARD	7.450,0 mm
	KEEL TO MASTHEAD	54,40 m
	LENGTH B/W PERPENDICULARS	265,00 m
	LENGTH OVERALL	274,30 m
	LENGTH REGISTERED	274,30 m
TONNAGES	FORMULA DWT	120.378 tons
	NET TONNAGE	41.937 tons

LOADLINE	DEADWEIGHT (MAXIMUM ASSIGNED)	**147.143 tons**
	DEADWEIGHT (NORMAL BALLAST)	**53.376 tons**
	DEADWEIGHT (SEGREGATED BALLAST)	**53.376 tons**
	DEADWEIGHT (TROPICAL)	**151.148 tons**
	DEADWEIGHT (WINTER)	**143.506 tons**
	DISPLACEMENT (LIGHTSHIP)	**20.322 tons**
	DISPLACEMENT (NORMAL BALLAST)	**73.698 tons**
	DISPLACEMENT (SEGREGATED BALLAST)	**73.698 tons**
	DISPLACEMENT (SUMMER)	**167.465 tons**
	DISPLACEMENT (TROPICAL)	**171.470 tons**
	DISPLACEMENT (WINTER)	**163.828 tons**
	DRAFT (LIGHTSHIP)	**2,51 m**
	DRAFT (NORMAL BALLAST)	**7,84 m**
	DRAFT (SEGREGATED BALLAST)	**7,84 m**
	DRAFT (SUMMER)	**17,02 m**
	DRAFT (TROPICAL)	**17,38 m**
	DRAFT (WINTER)	**16,67 m**
	DRAUGHT AFT (NORMAL BALLAST)	**9,30 m**
	DRAUGHT FORE (NORMAL BALLAST)	**6,30 m**
	FREEBOARD (LIGHTSHIP)	**21,36 m**
	FREEBOARD (NORMAL BALLAST)	**16,03 m**
	FREEBOARD (SEGREGATED BALLAST)	**16,03 m**
	FREEBOARD (SUMMER)	**6,85 m**
	FREEBOARD (TROPICAL)	**6,49 m**
	FREEBOARD (WINTER)	**7,20 m**
	FWA (SUMMER DRAFT)	**389,0 mm**
	TPC IMMERSION (SUMMER DRAFT)	**107,90 tons**

CAPACITIES	BALLAST	52.611 m3
	BUNKER	5.024 tons
CREW	MINIMUM MANNING REQUIRED (OFFICERS)	7
	MINIMUM MANNING REQUIRED (RATINGS)	8
	OFFICERS ACTUAL MANNING	11
	OFFICERS MANNING AGENT	
	OFFICERS NATIONALITY	SOUTH KOREA/SOUTH KOREA
	RATINGS ACTUAL MANNING	17
	RATINGS MANNING AGENT	
	RATINGS NATIONALITY	CHINA/MYANMAR
COMMUNICATION	CALL SIGN	9VGE2
	INMARSAT PHONE	356328310
	MMSI CODE	563 283 000
	MOBILE PHONE	6597866211
	SHIP EMAIL	
	SHIP FAX	356328311
	SHIP TELEX	INMA C: 456 328 312 A/B OJEW / 456 328 313 A/B
HISTORICAL INFO	DATE OF ORDER	1988 Jun 01
	KEEL LAID	1990 Sep 25
	YARD NUMBER	C/48

HISTORICAL INFO

FORMER NAMES	since 2005 Jun 22 FRONT LILLO
	since 2001 May 31 LILLO
FORMER FLAGS	since 2005 Jun 22 MARSHALL ISLANDS
	since 2004 Feb 23 NORWAY INTERNATIONAL REGISTER
	since 2001 May 31 LIBERIA
	since 1992 Feb 13 PANAMA

information provided by XVAS the Vessel Assessment System

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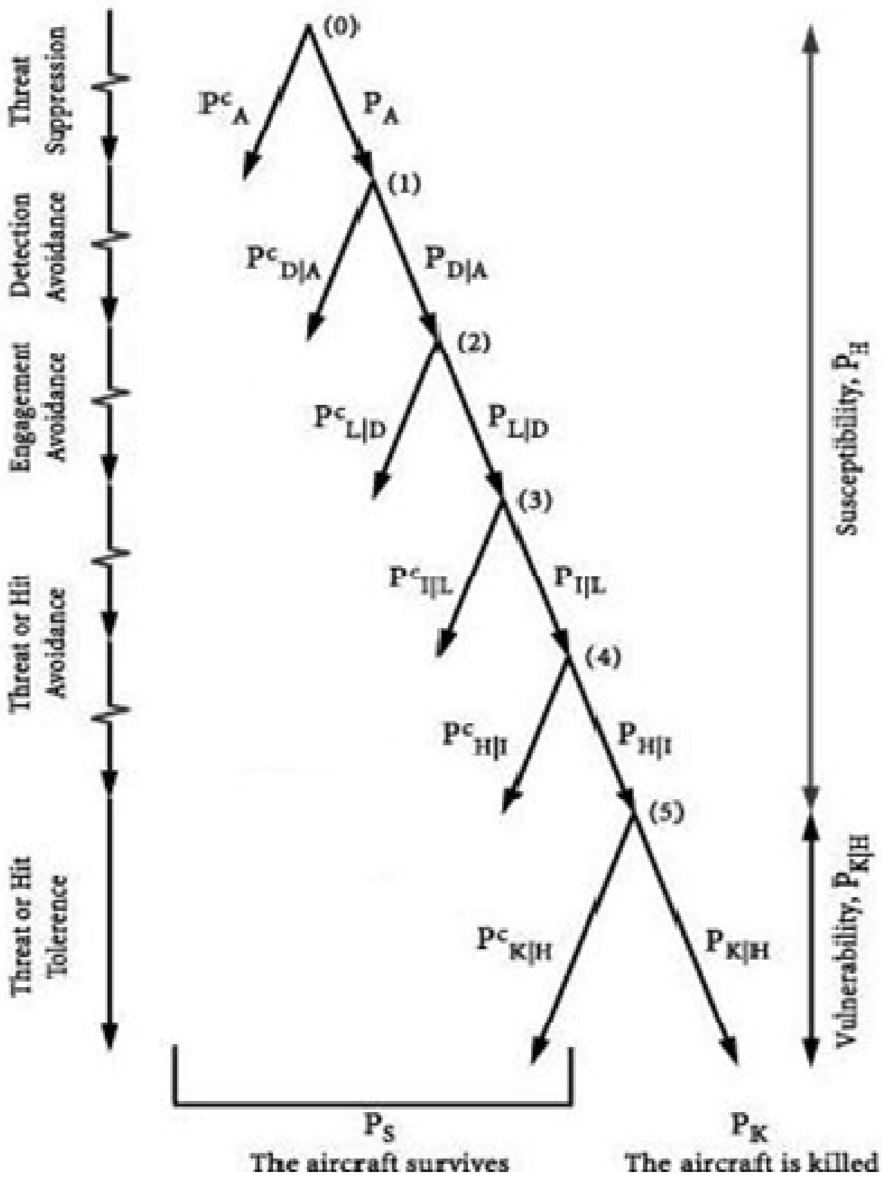
APPENDIX C. KILL TREE [9]



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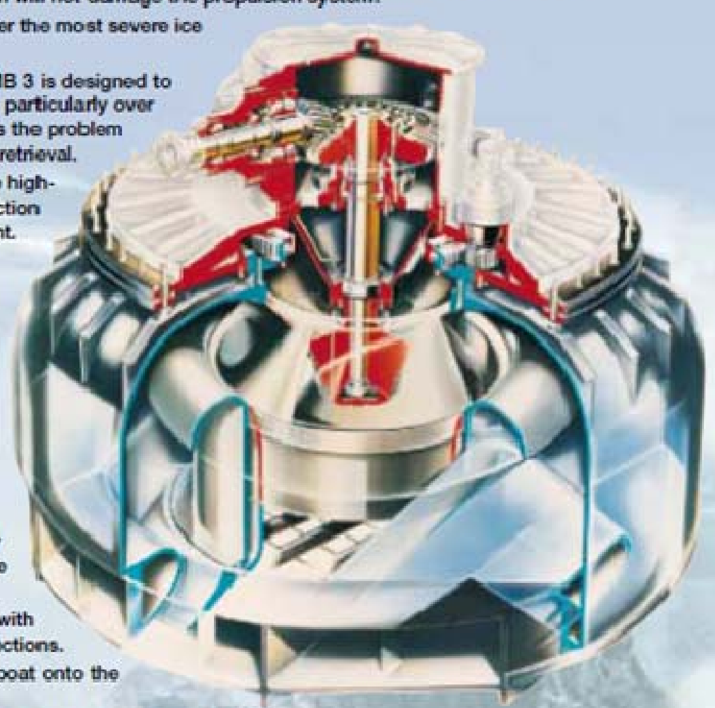
APPENDIX D. SCHOTTLE BRIDGE ERECTION BOAT [26]

Excerpts from product information sheet

The superiority of the bridge erection boat type MB 3 is attributable to its extensive operational capabilities and design features:

- The shallowest draught ever designed for a bridge erection boat (only 45 cm including protection skegs with completely filled fuel tank, fully equipped and 2 crew members) giving incomparable shallow water capabilities.
- The SCHOTTEL Pump-Jet propulsion system is based on a centrifugal pump, therefore it is extremely robust. The unit is highly resistant to dirt and sand, and cannot be damaged by any foreign bodies passing through.
- Full protection of the SCHOTTEL Pump-Jet due to its being totally incorporated in the hull. This means that grounding or collision with the transom stern will not damage the propulsion system.
- Permanent operational readiness, even under the most severe ice conditions.
- The SCHOTTEL bridge erection boat type MB 3 is designed to allow launch and retrieval by truck or trailer, particularly over rough ground on river banks. This eliminates the problem of awkward manoeuvres during launch and retrieval.
- SCHOTTEL Pump-Jet driven boats have the highest thrust of their type, therefore bridge erection is possible even in the strongest river current.
- Due to the low suction effect of the Pump-Jet divers can work below the running unit without being exposed to danger.
- The complete hull and Pump-Jets are manufactured of aluminium.



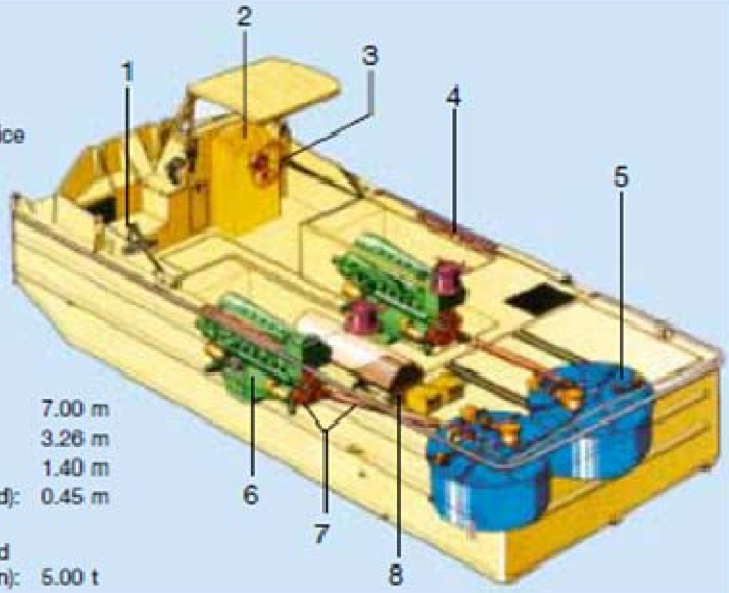
SCHOTTEL's bridge erection boat type MB 3 is superior on account of its capability to reduce bridge erection time to the shortest ever achieved. This capability results from the following features:

- The boat has been designed to comply fully with the requirements of all types of foldable floating bridge.
- The boat can be transported and launched with the same truck/trailer used for the bridge sections.
- The period for launching and retrieving the boat onto the carrier has been minimized to seconds.
- The aircooled engines can be started onshore allowing immediate and full operation upon launching.

The ease of handling and safe operation contribute to the superiority of the SCHOTTEL bridge erection boat type MB 3 because:

- The operator can easily learn how to manoeuvre the boat. Operation is as simple as driving a car.
- The special quick stop device behaves like a brake.
- Only one handwheel and one lever have to be operated to carry out any necessary manoeuvre.
- The unlimited thrust rotation through 360° in both directions assures the fastest, simplest and safest positioning of bridge sections.
- The hydraulic tensioning device enables the boat and the bridge section to be handled by two men only.
- The aircooled engines are freeze-proof and there is no risk of a water filter becoming clogged with sand.

Subassemblies
1 Loading device
2 Electrical system
3 Steering system
4 Rope stretching device
5 Pump-Jet
6 Diesel engine
7 Clutch / power transmission shaft
8 Fuel system



Main specifications

Length overall:	7.00 m
Beam:	3.26 m
Depth:	1.40 m
Draught (fully equipped):	0.45 m
Weight (hull lightweight welded aluminium construction):	5.00 t

The easily removable covers enable all the necessary maintenance work on the propulsion units to be carried out from above.

The optimally dimensioned and ergonomically favourable superstructure and deck equipment allow safe and easy operation even in night and winter service.

Power:	2 x KHD Diesel engines (aircooled with exhaust turbocharger and charge-air cooler) type BF 6 L 913 C (131 kW/178 h.p. each)
SCHOTTEL Pump-Jet:	Type SPJ 55 M
Steering:	Electrohydraulic SCHOTTEL steering system SST 622 with quick stop device
Speed:	above 30 km/h
Thrust:	22,000 N
Sound level max.:	85 dbA at control position
Designers:	SCHOTTEL

APPENDIX E. HARDWARE TRL DEFINITIONS [10]

Table 3-1. Hardware TRL Definitions, Descriptions, and Supporting Information
(Source: *Defense Acquisition Guidebook*)

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?

Table 3-1. Hardware TRL Definitions, Descriptions, and Supporting Information (Source: *Defense Acquisition Guidebook*) (Continued)

TRL	Definition	Description	Supporting Information
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space). Examples include testing the prototype in a test bed aircraft.	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.

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